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The Effect of Atmospheric Stability (Pasquil Stability) on the Distribution Radius and Concentration of CO2 Using Phast 8.22 Modeling from Oil and Gas Processing Facilities in Central Java

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ABSTRACT

The oil and gas industry sector is one of the largest contributors to CO_2 emissions, especially in oil and gas processing facilities. One of the locations of concern is the oil and gas processing facility in Central Java, which has produced and has the largest levels of CO_2 in Indonesia. The effect of atmospheric stability (Pasquill stability) on the radius of distribution and concentration of CO_2 from oil and gas processing facilities in Central Java using PHAST 8.22 modeling. The study compared two operating conditions, normal venting and emergency venting, and examined variations in atmospheric stability (Pasquill categories A, B, and D) and wind speed against CO_2 dispersion. The results showed that emergency venting conditions produce a greater radius of CO_2 distribution than normal venting. At a concentration of 5000 ppm, the radius of CO_2 distribution reached 17.06 meters for normal venting and 21.29 meters for emergency venting under atmospheric stability category D with a wind speed of 6.25 m/s. Hot weather conditions (temperature 35°C and humidity 60%) tend to increase the dispersion of CO_2, while rainy conditions (temperature 23°C and humidity 98%) slightly reduce the dispersion. Atmospheric stability and wind speed have a significant effect on CO_2 dispersion, where more stable atmospheric conditions (Category D) result in a wider distribution radius. High concentrations of CO_2 (5000 ppm) at a spread radius of 21.29 meters have the potential to cause health impacts if exposed for a long time.

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INTRODUCTION

The increase in greenhouse gas emissions, particularly carbon dioxide (CO_2), has become a pressing global issue that requires addressing. CO_2 is one of the main gases contributing to global warming and climate change. In Indonesia, the oil and gas industry is one of the largest contributors to CO_2 emissions, particularly at oil and gas processing facilities, which still release CO_2 as a pollutant into the air through chimney ventilation. One location of concern is the oil and gas processing facility in Central Java, which has been producing and has the highest CO_2 levels in Indonesia.

Table 1. Oil and gas fields with the largest carbon emissions (Anisatul Umah, 2021)

No	Perusahaan	Lapangan Migas	%	Status
1	Medco E&P	Lapangan Kuala Langsa	81	Belum berproduksi
2	Pertamina EP	Blok East Natuna	80	Belum berproduksi
3	XYZ	Blok di Jawa Tengah	68	Sudah Berproduksi
3	Medco Koridor	Lapangan South Jambi	60	Sudah Berproduksi
4	Medco E&P	Lapangan Arung-Nowera	60	Belum berproduksi
5	Medco E&P	Lapangan Singa	38	Sudah Berproduksi
6	Pertamina EP	Lapangan Jambaran Tiung Biru (JTB)	35	Sudah Berproduksi
7	BP Berau	Lapangan Tangguh	12	Sudah Berproduksi

This location was chosen as the object of this research because its CO_2 venting activity has the potential to negatively impact the environment and the health of the surrounding community, particularly considering the location of the production facility's operations near rice fields and residential areas.

Figure 1. Image of the production operations location

Atmospheric stability, which can be classified using the Pasquill Stability method, is a key factor influencing the dispersion of air pollutants. Atmospheric stability describes the tendency of the atmosphere to inhibit or facilitate vertical air movement, which in turn affects the distribution and concentration of pollutants such as CO_2. Under stable atmospheric conditions, pollutants tend to accumulate near their emission sources, leading to higher local concentrations and an expanded dispersion radius. Conversely, under unstable atmospheric conditions, pollutants disperse and dilute more rapidly. Therefore, understanding the influence of atmospheric stability on CO_2 dispersion is essential for predicting potential environmental and health impacts.

This study employs PHAST 8.23 modeling, a software tool designed to simulate the dispersion of pollutants in the atmosphere. The modeling enables a comprehensive analysis of the dispersion radius and CO_2 concentrations under varying atmospheric stability conditions. By utilizing local meteorological data and operational parameters of oil and gas facilities, the model provides an accurate representation of how CO_2 disperses in the air and the extent of its impact on the surrounding environment. The selection of PHAST 8.23 is based on its capability to integrate complex factors such as wind speed, temperature, humidity, and atmospheric stability within a single simulation.

Gas dispersion modeling is an important tool for predicting the spread of pollutants in the atmosphere. Various dispersion modeling software packages have been developed, one of which is PHAST (Process Hazard Analysis Software Tool). PHAST is a reliable and widely used software in the oil and gas industry for risk and safety analysis (DNV GL, various years). PHAST offers several advantages over other dispersion models, including:

a) The ability to simulate various types of gas releases, including heavy gas releases (gases heavier than air, such as CO_2).
b) Consideration of gas buoyancy effects and the influence of ground surface characteristics on dispersion.
c) The capability to simulate dispersion under various atmospheric conditions, including stable and unstable conditions.
d) Mathematically robust models that have been tested and validated using experimental data and field observations.

The theoretical rationale of this study is to address the knowledge gap regarding the influence of atmospheric stability on CO_2 dispersion in the vicinity of oil and gas facilities. Practically, the findings of this study are expected to serve as a basis for policymaking and mitigation measures aimed at reducing the negative impacts of CO_2 emissions. For example, by understanding CO_2 dispersion patterns, facility operators can optimize venting schedules or implement carbon capture and storage (CCS) technologies to reduce emissions. In addition, this study may provide recommendations to government authorities and local communities regarding necessary adaptation measures to minimize health and environmental risks.

The impacts of CO_2 emissions are not only global but also local. Communities living near oil and gas facilities, including farmers working in agricultural areas, may be exposed to high concentrations of CO_2. Long-term exposure to elevated CO_2 levels can lead to respiratory disorders and other health problems. Therefore, this study also has strong social relevance, as it aims to protect public health and the environment surrounding oil and gas facilities. By integrating both theoretical and practical approaches, this research is expected to offer comprehensive solutions to address CO_2 emission issues in the oil and gas sector.

References supporting this study include Pasquill's (1961) work on atmospheric stability classification, Turner's (1994) research on atmospheric pollutant dispersion, and reports from the Intergovernmental Panel on Climate Change (IPCC, 2021) concerning the impacts of CO_2 emissions on climate change. In addition, similar case studies conducted at oil and gas facilities in other countries, such as the study by Smith et al. (2019) on the implementation of CCS technology, serve as important references. Accordingly, this study is expected to make a significant contribution to both scientific knowledge and more sustainable practices within the oil and gas industry.

Considering the urgency of addressing CO_2 emissions and their potential impacts on the environment and public health, this study is both relevant and important to conduct. The results are expected to provide a foundation for the development of more environmentally friendly policies and technologies, as well as to enhance awareness of the importance of CO_2 emission management in the oil and gas sector.

LITERATURE REVIEW

Fundamental Theory

Atmospheric Stability (Pasquill Stability):

Atmospheric stability refers to the tendency of the atmosphere to inhibit or facilitate the dispersion of pollutants. The Pasquill method classifies atmospheric stability into several categories (A–F) based on wind speed, solar radiation, and cloud cover conditions (Pasquill, 1961; Turner, 1994).

Table 2. Pasquill Stability Classes

Stability Class	Definition	Stability Class	Definition
A	Very unstable conditions	D	Neutral conditions
B	Moderately unstable conditions	E	Slightly stable conditions
C	Slightly unstable conditions	F	Moderately stable conditions

The determination of meteorological stability classes defines the Pasquill Stability Classes.

Table 3. Meteorological Conditions Defining Pasquill Stability Classes

Wind Speed (m/s)	Daytime Conditions			Nighttime Conditions		Any Time
	Strong	Moderate	Weak	Cloudy (≥4/8)	Clear (≤3/8)	Overcast
< 2	A	A–B	B	E	F	D
2–3	A–B	B	C	E	F	D
3–5	B	B–C	C	D	E	D
5–6	C	C–D	D	D	D	D
> 6	C	D	D	D	D	D

Atmospheric Pollutant Dispersion:

Pollutants such as CO_2 are dispersed in the atmosphere through advection (horizontal movement) and diffusion (vertical movement). Atmospheric stability influences the rate of diffusion and the concentration of pollutants in the air (Seinfeld & Pandis, 2016).

Environmental and Health Impacts of CO_2:

As a greenhouse gas, CO_2 can affect air quality, ambient temperature, and human health. High concentrations of CO_2 in agricultural areas may influence plant growth and land productivity (IPCC, 2021; Smith et al., 2017).

Relationship between Atmospheric Stability and CO_2 Dispersion

Stable Atmospheric Conditions:

Under stable atmospheric conditions (Pasquill categories E–F), pollutant dispersion is inhibited, resulting in higher CO_2 concentrations near emission sources (Holmes & Morawska, 2006).

Unstable Atmospheric Conditions:

Under unstable atmospheric conditions (Pasquill categories A–C), pollutants disperse more rapidly, leading to lower CO_2 concentrations and a wider spatial distribution in the atmosphere (Turner, 1994).

Influence of Meteorological Parameters:

Meteorological factors such as wind speed, air temperature, and humidity significantly influence atmospheric stability and CO_2 dispersion patterns (Seinfeld & Pandis, 2016).

PHAST 8.22 as a Modeling Tool:

PHAST 8.22 is a software application used to model gas dispersion in the atmosphere based on emission parameters, atmospheric conditions, and topographical characteristics (DNV, 2020).

Modeling Inputs and Outputs:

Model inputs include CO_2 emission data, meteorological parameters, and oil and gas facility characteristics. The modeling outputs consist of CO_2 dispersion patterns and concentration levels in the surrounding environment (Holmes & Morawska, 2006).

The theoretical foundation of this study is Atmospheric Dispersion Theory, supported by Meteorological Theory and principles of Thermodynamics. These theories provide a strong conceptual basis for understanding and analyzing the influence of atmospheric stability (Pasquill Stability) on CO_2 dispersion patterns. PHAST 8.22 modeling represents a practical implementation of these theoretical principles.

PHAST's capabilities and features in gas dispersion modeling include the dispersion models implemented within the software (e.g., the Unified Dispersion Model) (DNV GL, latest version, *PHAST Technical Manual*). The advantages and limitations of PHAST compared with other gas dispersion modeling software (e.g., AERMOD and CALPUFF) are discussed based on prior studies (Hanna & Baja, 2012).

Table 4. Comparison of Gas Dispersion Modeling Software

No.	Specification	PHAST	AERMOD	CALPUFF
1	Spatial scale	Short-range	Medium-range	Medium- to long-range
2	Application focus	Oil and gas / chemical industry	Urban and general industrial areas	Areas with complex topography

No.	Specification	PHAST	AERMOD	CALPUFF
3	Meteorological effects	Simplified	Detailed	Highly detailed (multi-day effects)
4	Cost	Commercial	Free	Free
5	Physical complexity	High for specific releases	General	High for environmental applications

RESEARCH METHODOLOGY

This study employs a quantitative approach using simulation and correlational analysis methods. Simulations were conducted using PHAST 8.22 software to model the dispersion of carbon dioxide (CO_2) released from an oil and gas processing facility in Central Java. The correlational approach was applied to analyze the relationship between atmospheric stability and CO_2 dispersion patterns.

The study population includes all possible weather conditions and CO_2 release scenarios that may occur in the vicinity of the oil and gas processing facility. Purposive sampling was used to select representative weather scenarios, considering factors such as wind speed, air temperature, humidity, and atmospheric stability (Pasquill–Gifford classes). Meteorological data were obtained from the Prediction of Worldwide Energy Resources (NASA), while operational data from the oil and gas processing facility were used as modeling parameters.

Data collection methods involved the use of secondary data, including meteorological data, facility operational data, and topographical information surrounding the study area. Simulations using PHAST 8.22 were performed by inputting key parameters such as CO_2 emission rate, stack height, wind speed, and atmospheric conditions. Simulation results were analyzed using descriptive statistical methods to illustrate CO_2 dispersion patterns in the form of contour maps and gas dispersion radii.

To validate the simulation results, comparisons were made with previous studies, along with sensitivity analyses of key variables influencing CO_2 dispersion. Statistical tests such as Pearson correlation analysis were applied to examine the relationships between meteorological factors and simulation outputs, while linear regression analysis was used to assess the influence of these variables on the extent of CO_2 dispersion.

RESULTS

This study analyzes the dispersion patterns of carbon dioxide (CO_2) gas released from an oil and gas processing facility using PHAST 8.22 modeling. Simulations were conducted under two main scenarios, namely normal venting and emergency venting, while considering variations in meteorological conditions such as temperature, humidity, and wind speed. The simulation results indicate that atmospheric stability plays a crucial role in determining both the dispersion distance and concentration of CO_2.

Under normal venting conditions, the released CO_2 disperses more widely, with dispersion radii reaching 17.06 m at a concentration of 5,000 ppm and 4.68 m at 30,000 ppm. In contrast, under emergency venting conditions, the release of a large volume of CO_2 results in increased gas concentrations near the emission source, with dispersion radii reaching 21.29 m at 5,000 ppm and 2.50 m at 30,000 ppm.

In addition, wind speed significantly influences dispersion patterns. High wind speeds (6.25 m/s) promote wider gas dispersion, whereas low wind speeds restrict gas movement and increase concentrations near the emission source. Rainy conditions with high humidity (98%) tend to inhibit dispersion, while hot weather with lower humidity (60%) allows the gas to disperse more extensively.

DISCUSSION

Atmospheric Stability Conditions and Their Influence on CO_2 Dispersion

1. Under hot weather conditions (humidity 60%, temperature 35°C), the atmosphere tends to be more unstable (Pasquill categories A–D), resulting in wider CO_2 dispersion. This is evidenced by longer dispersion distances, particularly under high wind speeds (6.25 m/s, category D). Under normal venting conditions (Case 1), CO_2 dispersion distances reached 17.06 m (5,000 ppm), 4.68 m (30,000 ppm), and 0.83 m (100,000 ppm).
2. Under rainy weather conditions (humidity 98%, temperature 23°C), the atmosphere tends to be more stable (Pasquill categories E–F), leading to more limited CO_2 dispersion. Under normal venting conditions (Case 1), dispersion distances reached 16.87 m (5,000 ppm), 4.58 m (30,000 ppm), and 0.81 m (100,000 ppm).

CO_2 Dispersion Patterns Based on PHAST 8.22 Modeling

1. CO_2 dispersion patterns vary depending on concentration levels and wind speed. At lower concentrations (5,000 ppm), CO_2 disperses over longer distances, whereas at higher concentrations (30,000 ppm and 100,000 ppm), CO_2 tends to remain concentrated near the emission source.
2. Under emergency venting conditions (Case 2) with a wind speed of 6.25 m/s (category D), CO_2 dispersion distances reached 21.29 m (5,000 ppm), 2.50 m (30,000 ppm), and 0.48 m (100,000 ppm).
3. Higher wind speeds (6.25 m/s) enhance CO_2 dispersion, particularly at lower concentration levels.

Differences in CO_2 Dispersion Patterns between Normal Venting and Emergency Venting

1. Under normal venting conditions (Case 1), CO_2 release is more controlled, resulting in wider dispersion, especially at lower concentrations. Under hot weather conditions with a wind speed of 6.25 m/s, the dispersion distance reached 17.06 m at 5,000 ppm.
2. Under emergency venting conditions (Case 2), the release of a large volume of CO_2 causes high concentrations near the emission source, leading to shorter dispersion radii. Under hot weather conditions with a

wind speed of 6.25 m/s, dispersion distances were only 2.50 m at 30,000 ppm and 0.48 m at 100,000 ppm.

Variations in CO_2 Concentration and Safety Thresholds

1. At a concentration of 100,000 ppm, CO_2 dispersion distances are very short (0.24–0.83 m), indicating that the pollutant is highly concentrated near the emission source. This concentration exceeds the short-term exposure limit (30,000 ppm according to ACGIH, 2021) and may pose serious health risks, including shortness of breath, dizziness, and loss of consciousness.
2. At a concentration of 5,000 ppm, CO_2 dispersion distances are wider (11.56–21.29 m); however, long-term exposure at this level still requires caution.

CONCLUSIONS

Based on the simulation results, the following conclusions can be drawn:

1. Atmospheric stability significantly affects CO_2 dispersion, with unstable atmospheric conditions (hot weather) facilitating wider dispersion, while stable conditions (rainy weather) inhibit dispersion.
2. PHAST 8.22 modeling effectively predicts CO_2 dispersion patterns, showing that lower concentrations result in wider dispersion radii, whereas higher concentrations remain more localized near the emission source.
3. Emergency venting conditions pose a higher risk of elevated CO_2 concentrations near the emission source, particularly under low wind speed conditions.
4. High CO_2 concentrations near emission sources may exceed safety thresholds, highlighting the need for mitigation measures to reduce health risks.

RECOMMENDATIONS

1. Improve venting system design to reduce CO_2 flow rates during emergency venting.
2. Develop real-time CO_2 emission monitoring systems.
3. Plant CO_2-absorbing vegetation around the facility (e.g., rain trees/Trembesi).
4. Establish buffer zones to minimize CO_2 exposure to surrounding communities.
5. Conduct awareness programs for workers and local residents regarding safe activity distances around venting areas.
6. Perform further studies to model CO_2 and other hazardous gas dispersion under various meteorological and operational scenarios.

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